

1WGA J1226.9+3332 : A HIGH REDSHIFT CLUSTER DISCOVERED BY *CHANDRA*I. CAGNONI<sup>1,2</sup>, M. ELVIS<sup>2</sup>, D.-W. KIM<sup>2</sup>, P. MAZZOTTA<sup>2,3</sup>, J.-S. HUANG<sup>2</sup>  
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## ABSTRACT

We report the detection of 1WGA J1226.9+3332 as an arcminute scale extended X-ray source with the *Chandra* X-ray Observatory. The *Chandra* observation and R and K band imaging strongly support the identification of 1WGA J1226.9+3332 as a high redshift cluster of galaxies, most probably at  $z = 0.85 \pm 0.15$ , with an inferred temperature  $kT = 10^{+4}_{-3}$  keV and an unabsorbed luminosity (in a  $r = 120''$  aperture) of  $1.3^{+0.16}_{-0.14} \times 10^{45}$  erg s<sup>-1</sup> (0.5–10 keV). This indication of redshift is also supported by the K and R band imaging, and is in agreement with the spectroscopic redshift of 0.89 found by Ebeling et al. (2001). The surface brightness profile is consistent with a  $\beta$ -model with  $\beta = 0.770 \pm 0.025$ ,  $r_c = (18.1 \pm 0.9)''$  (corresponding to  $101 \pm 5$  kpc at  $z = 0.89$ ), and  $S(0) = 1.02 \pm 0.08$  counts arcsec<sup>-2</sup>. 1WGA J1226.9+3332 was selected as an extreme X-ray loud source with  $F_X/F_V > 60$ ; this selection method, thanks to the large area sampled, seems to be a highly efficient method for finding luminous high  $z$  clusters of galaxies.

*Subject headings:* galaxies: high-redshift — galaxies: clusters: general — galaxies: clusters: individual (1WGA J1226.9+3332) — X-rays: galaxies: clusters — X-rays: individual (1WGA J1226.9+3332)

## 1. INTRODUCTION

Clusters of galaxies are good tracers of the large scale structure of the matter distribution in the universe. The standard models of structure formation predict that the cluster distribution and evolution is fully determined by the spectrum of primordial perturbations and cosmological parameters  $\Omega_0$  and  $\Lambda$  (e.g. Press & Schechter 1974; and later works), thus observations of high redshift clusters constrain these parameters (e.g., Oukbir & Blanchard 1992). Moreover X-ray measurements of high redshift clusters of galaxies can place strong constraints on the thermodynamic evolution of the intracluster medium (ICM). For example the Luminosity-Temperature ( $L_X - T$ ) relation at different redshifts probes the interrelated evolution of the cluster baryon mass and the total mass (e.g. Kaiser 1991; Evrard & Henry 1991; and later works). Furthermore X-ray observations of the Sunyaev-Zeldovich effect of a sample of objects at different  $z$  may be used to obtain an independent estimate of  $H_0$  (for a review see e.g., Birkinshaw 1999).

Given this potential wealth of information in the past few years a great effort has been made to search for high redshift clusters of galaxies (e.g. Rosati et al. 1998; Vikhlinin et al. 1998). Among the different methods, X-ray surveys have played the most important role, but no method allowed the identification of more than a handful of clusters at  $z > 0.8$ . The finding of clusters from the X-ray data was complicated mainly by the low spatial and/or spectral resolution of the previous X-ray missions. *Einstein* and *ROSAT* marked an impor-

tant step in the study of clusters but thanks to sub-arcsecond *Chandra* spatial resolution it is now possible to distinguish easily between point sources and the more diffuse X-ray emission from clusters at any redshift.

We present the *Chandra* observation of 1WGA J1226.9+3332. This source is one of 16 peculiar *ROSAT* PSPC sources selected for their extremely high X-ray to optical flux ratio (Cagnoni et al. 2000; Cagnoni et al., in prep.). 1WGA J1226.9+3332 is a bright ( $F_{0.1-2.4\text{keV}} > 10^{-13}$  erg cm<sup>-2</sup> s<sup>-1</sup>) WGACAT (White, Giommi & Angelini 1994) source with blank fields, i.e. no optical counterparts on the Palomar Observatory Sky Survey to  $O=21.5$ . The extreme  $F_X/F_V$  ratio that follows from this is incompatible with all major and common classes of extragalactic sources, including normal quasars, AGNs, normal galaxies and nearby clusters of galaxies (Maccaro et al. 1988). Possibilities for the nature of these ‘blanks’ (Cagnoni et al. in prep.) include:

(a) Quasar-2s, i.e. high luminosity, high redshift heavily obscured quasars, the bright analogs of Seyfert 2s; (b) Low Mass Seyfert-2s, that is AGNs powered by a low mass obscured black hole (i.e. obscured Narrow Line Sy 1); (c) AGNs with no big blue bump, e.g. ADAFs; (d) Isolated Neutron Stars undergoing Bondi accretion from the ISM (Madau & Blaes 1994); (e)  $\gamma$ -ray burst X-ray afterglows, (f) failed clusters, in which a large overdensity of matter has collapsed but has not formed galaxies (Tucker, Tananbaum & Remillard 1995); and, most relevant to this paper, (g) high redshift clusters of galaxies.

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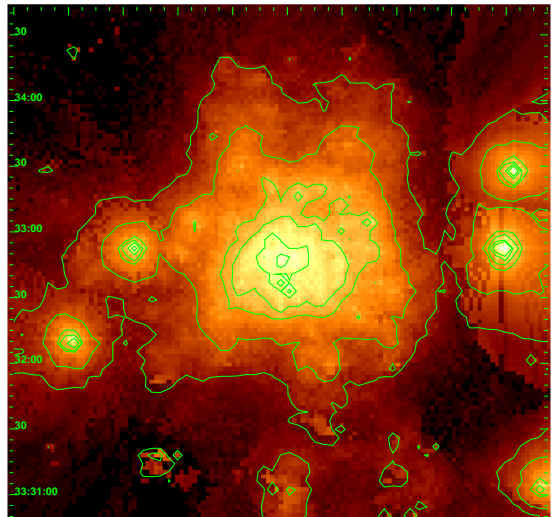
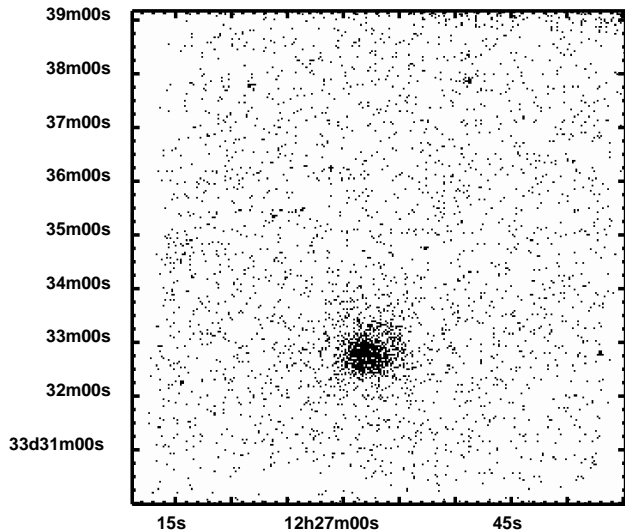


FIG. 1.— *Chandra* view of 1WGA J1226.9+3332: (a) cleaned data (see text) in the whole S3 chip and (b) zoom of the cluster (smoothed and background subtracted).

Here we present strong evidence that 1WGA J1226.9+3332 is indeed a high redshift cluster.

We will use  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0.5$ ; errors in the paper represent  $1\sigma$  confidence levels, unless explicitly stated otherwise.

## 2. CHANDRA OBSERVATIONS

1WGA J1226.9+3332 was one of two ‘blanks’ for which we obtained Cycle 1 *Chandra* (Weisskopf et al., 1996) observing time. It was observed in ACIS-S configuration (Garmire et al., in prep.) with the backside illuminated S3 chip for a total useful exposure time of 9832.3 s. The data was cleaned as described in Markevitch et al. (2000a) and for the spectral and image analysis we used the latest available ACIS background dataset (Markevitch et al. 2000b).

### 2.1. Spatial analysis

To maximize the signal-to-noise ratio, we extracted the image in the 0.5–5 keV band (Fig. 1a and b). Along with a number of faint point-like sources, 1WGA J1226.9+3332 is clearly seen as an extended source on an arcminute scale. It shows azimuthal symmetry, except for a possible excess to the north-west,  $\sim 40''$  from the cluster center.

After subtracting the background, from the same regions in a normalized ACIS background map (Markevitch et al. 2000b), we extracted the X-ray surface brightness profile (Fig. 2) in concentric annular regions centered on the X-ray emission peak and chosen in order to have 20 counts per annulus. The profile appears to be smooth without any obvious central excess related to a cooling flow (Figs. 1 and 2).

We fitted the surface brightness profile with a standard  $\beta$  model<sup>2</sup> (Cavaliere & Fusco-Femiano 1976) using the *Sherpa* (Siemiginowska et al., in prep.) modeling and fitting tool from the CXC analysis package CIAO 2.0 (Elvis et al., in

prep.). We obtained best fit values of  $\beta = 0.770 \pm 0.025$ ,  $r_c = (18.1 \pm 0.9)''$  (corresponding to  $101 \pm 5 \text{ kpc}$  at  $z = 0.89$ ), and  $S(0) = 1.02 \pm 0.08 \text{ counts arcsec}^{-2}$  with a  $\chi^2$  of 27.5 for 26 degrees of freedom (d.o.f.). The excess to the north-west of the cluster is also visible in the radial profile; a drop of the surface brightness at  $\sim 40''$  is present in the radial profile for the north-west sector. Similar features in the surface brightness radial profiles were detected by *Chandra* in nearby clusters (e.g. Markevitch et al. 1999; 2000a; 2001, Vikhlinin et al. 2001; Mazzotta et al. 2001) and interpreted as signs of subclump motion.

### 2.2. Spectral analysis

We extracted an overall spectrum in a circle with  $r = 120''$  in the 0.5–10 keV band in PI channels, corrected for the gain difference between the different regions of the CCD. The spectrum (Fig. 3) contains  $\sim 1100$  net counts and we binned it in order to have 100 counts per bin<sup>3</sup>. Both the effective area file (ARF) and the redistribution matrix (RMF) were computed by weighting each position dependent ARF’s and RMF’s by the X-ray brightness. We fitted the spectrum in the 0.5–10 keV range with an absorbed Raymond-Smith model (Raymond & Smith, 1977) using *Sherpa*. The source redshift is treated as unknown and, because of the low statistics, no iron line or other line complex features are expected to be visible.

In order to get an estimate of the temperature, we fixed the equivalent hydrogen column density to the Galactic value ( $N_H = 1.38 \times 10^{20} \text{ cm}^{-2}$ , Stark et al. 1992), the metal abundance to 0.3 times the Solar value, and we draw confidence levels for the  $T$  and  $z$  (Fig. 4). We find a best fit value of  $kT = 10.24 \text{ keV}$  and  $z = 0.85$  ( $\chi^2$  is 18.68 for 20 d.o.f.)<sup>4</sup>. However, as shown in Fig. 4, these values are not well constrained.

While submitting this paper we found that the same object had been independently identified as a cluster of galaxies in the WARPS survey (Ebeling et al. 2001) and observed for

<sup>2</sup> $S(r) = S(0)[1 + (r/r_c)^2]^{-3\beta+1/2}$

<sup>3</sup>A smaller binning, e.g. as in Fig. 3, leads to similar results

<sup>4</sup>Normalizing the background map using an area of 1WGA J1226.9+3332 observation without sources (7.56% lower background) consistent results are obtained:  $kT = 11.94 \text{ keV}$  and  $z = 0.87$

Sunyaev-Zel'dovich effect measurement by Joy et al. (2001). The cluster spectroscopic redshift measured by Ebeling et al. (2001) is  $z = 0.89$ , which is within the errors of our estimate based on *Chandra* and optical/IR constraints (see Section 4). Fixing the redshift to this value we obtain a temperature of  $kT = 10.47_{-3}^{+4}$  keV ( $kT=12.07$  keV using a normalized background), which is in good agreement with that obtained from the Sunyaev-Zel'dovich measurement by Joy et al. (2001) ( $kT = 10.0_{-1.5}^{+2.0}$  keV). The absorbed 0.5-2.0 keV flux<sup>5</sup> in a  $r = 120''$  aperture is  $(3.0 \pm 0.3) \times 10^{-13}$  erg cm<sup>-2</sup> s<sup>-1</sup>, consistent with the Ebeling et al. (2001) PSPC measurement; the 0.5-10.0 keV absorbed flux in the same aperture (Table 1) is  $(8.03_{-0.88}^{+0.96}) \times 10^{-13}$  erg cm<sup>-2</sup> s<sup>-1</sup>. For  $z=0.89$  the unabsorbed bolometric and 0.5-2.0 keV band luminosities are  $L = (2.2 \pm 0.2) \times 10^{45}$  erg s<sup>-1</sup> and  $L_{X(0.5-2.0)} = (4.4 \pm 0.5) \times 10^{44}$  erg s<sup>-1</sup> respectively.

### 3. OPTICAL, INFRARED AND RADIO OBSERVATIONS

We obtained an R-band image of the 1WGA J1226.9+3332 field on Feb. 2, 1997 using the SAO 1.2 m telescope on Mt.Hopkins. A  $R = 20.4 \pm 0.2$  galaxy is detected less than  $1''$  from the X-ray centroid (Table 1).

A K-band image of the field was obtained using NSFCam at the NASA IRTF on Jan. 31, 2000. The same galaxy is also seen, but is much brighter at  $K=15.5$  (Fig. 5) isophotal magnitude. The K-band magnitude within the core radius of the X-ray source is  $K=15.4$ , implying that little large scale IR emission is present. The R-K color of this object is 5.1 with an estimated uncertainty of 0.3 mag due to the poor image quality in both K- and R-band.

Comparing R and K-band images, it is clear that there are many more objects detected in the K- than in the R-band. We detect 23 objects with  $K < 19.5$  mag in the  $1.5' \times 1.5'$  image using the source extractor software (SExtractor, Bertin & Arnouts 1996) versus only 4 at R. The star/galaxy classification was carried out morphologically using the Kron radius (Bertin & Arnouts 1996), and 3 objects are classified as pointlike. These objects are also detected in the R-band and have bluer colors ( $R-K < 4.2$ ) than the extended objects; we argue they are stars. We should not have to worry about the star contamination of the sample since there are very few stars with  $K > 16$  (e.g. Glazebrook et al. 1995). The rest of the morphologically extended objects are galaxies. These, including the bright one located at the X-ray centroid, have very similar red colors ( $4.5 < R-K < 6.5$ ), implying that they likely have similar redshifts and be-

long to a cluster. A high- $z$  cluster, CIG J0848+4453, at  $z=1.27$  was detected in a near-IR field survey using similar color criteria in an over-dense region (Stanford et al 1997). The apparent asymmetry of the galaxy distribution may be an artifact of the longer exposure time at the center of the K-band mosaic image which is offset from the X-ray centroid.

The galaxy surface density in the K-band image is clearly high (Fig. 5). We generate K-band galaxy number counts in our field in the range  $15 < K < 19.5$ , and compare them with those obtained from the near-IR field survey in this range (Gardner et al. 1993, Saracco et al. 1997, Huang et al. 1997, Minezaki et al. 1998, Huang et al. 2000) with their coverage ranging from 200 arcmin<sup>2</sup> to 10 deg<sup>2</sup>. The number counts obtained from our image are substantially higher ( $> 10\sigma$ , a factor of 100 at  $K=19$ ) than those from the field surveys. Such a large excess cannot be due to Poisson statistics or magnitude errors.

Both the high density and the similar (extremely red) colors for these galaxies thus imply that they are likely to be members of a cluster.

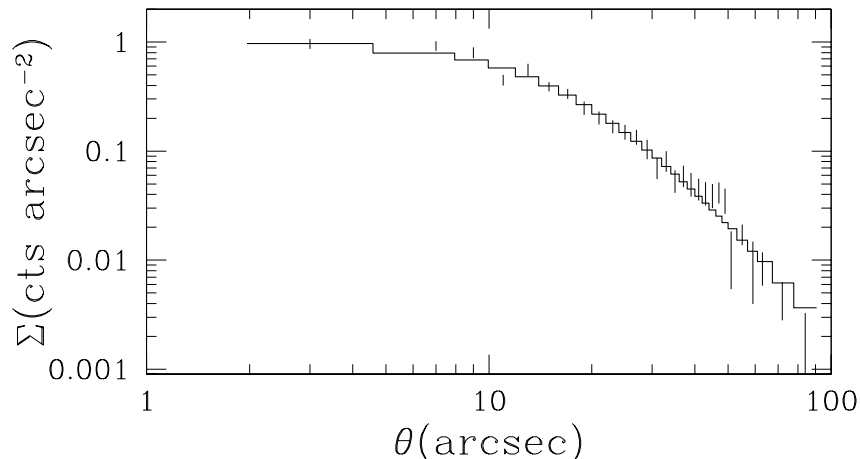
The FIRST survey detected a faint  $3.61 \pm 0.18$  mJy source at 1.4 GHz (Becker, White & Helfand, 1995) close to the center of the X-ray emission (Table 1). The radio source is pointlike ( $\text{FWHM} \leq 0.91''$ ,  $\leq 16$  kpc at  $z = 0.85$ ) and has a luminosity  $L_R(z = 0.85) \sim 6.6 \times 10^{24}$  W Hz<sup>-1</sup>, compatible with low luminosity radio-loud AGNs (e.g. Zirbel & Baum, 1995).

### 4. DISCUSSION AND CONCLUSION

*Chandra* has shown that 1WGA J1226.9+3332 is an extended X-ray source, with a hard, high temperature thermal spectrum. Optical and IR imaging has shown that 1WGA J1226.9+3332 has faint optical/IR counterparts. A cluster of galaxies is the only known type of object that could fit such a description. Moreover the K-band image shows a strong excess of galaxies compared with field counts at  $K > 17$  (Fig. 5) around 1WGA J1226.9+3332. Physical clustering is the only possible explanation. Several lines of argument go on to suggest that it is a high redshift cluster of galaxies. Below we list these arguments and try to constrain its temperature and redshift. These results are summarized in Figure 4.

(1) The *Chandra* X-ray profile is well fitted by a  $\beta$  model with  $\beta=0.77$ , a value in agreement with a typical relaxed cluster (e.g. Jones & Forman, 1999 and references therein). Moreover, if the cluster redshift is  $0.7 < z < 1.2$ , then the observed angular core radius,  $r_c = (18.1 \pm 0.9)''$  ( $101 \pm 5$  kpc at  $z = 0.89$  with the assumed cosmology), corresponds to a linear size of

<sup>5</sup>The main component in the flux error is the uncertainty on the cluster temperature (quoted in the text); using the  $\pm 1\sigma$  values on  $T$  we derive an error of +11% -12% on the flux. Other contributions come from the normalization chosen for the background ( $\pm 9\%$ ), from the fraction of counts lost using the  $r = 120''$  aperture assuming a  $\beta$ -profile ( $\pm 5\%$ ) and from the Poisson error on the counts ( $\pm 3\%$ )



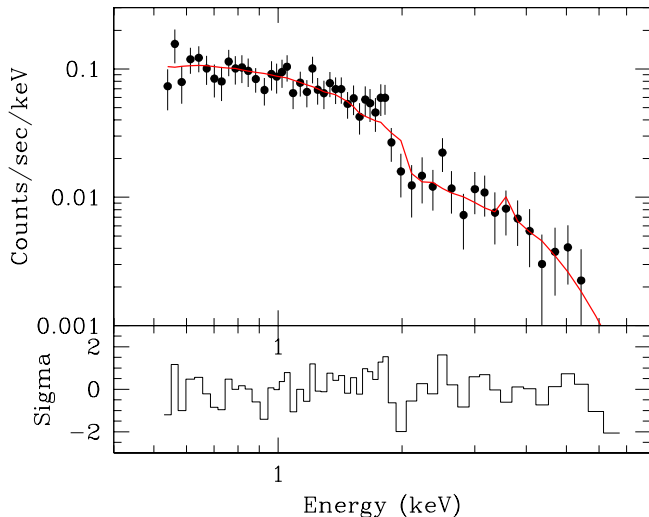


FIG. 3.— *Chandra* ACIS Spectrum and residuals to a Raymond-Smith model with  $kT = 10.23$  keV and  $z = 0.89$ . The spectrum was binned, for display purposes, to obtain a minimum of 30 counts per bin.

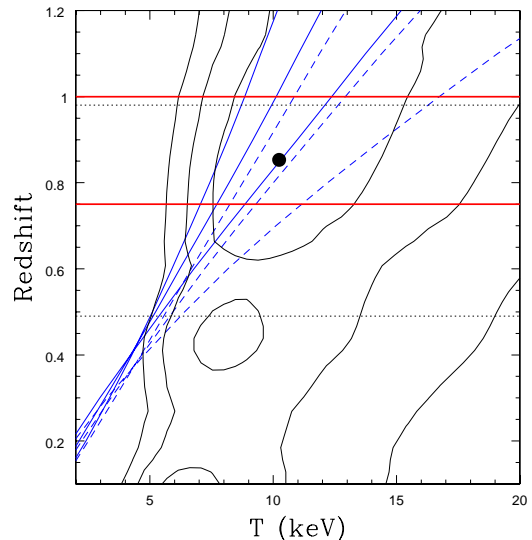


FIG. 4.— The contours of the fit with a Raymond-Smith plasma at 1, 2 and 3  $\sigma$ . The three blue solid lines represent the luminosity-temperature relation (Markevitch 1998) for  $q_0 = 0.5$  and the three blue dashed lines for  $q_0 = 0$ . The red lines represent the limits on the redshift obtain from the R-K color of the brightest object assuming it is a first ranked elliptical (Coleman, Wu & Weedman 1980), while the dotted lines are the limits from the magnitude of the first ranked elliptical (see text). The big dot corresponds to the best fit to the *Chandra* spectrum.

$90 < r < 150$  kpc for any value of  $\Omega$  ( $130 < r < 220$  kpc for any value of  $\Omega$  for  $H_0 = 50$  km s $^{-1}$  Mpc $^{-1}$ ), values consistent with a typical relaxed cluster.

(2) It is well known that clusters of galaxies follow a well-defined Luminosity-Temperature relation (e.g. Markevitch 1998 and reference therein). Recently it has been shown that the local  $L_X - T$  relation does not evolve (or is consistent with little evolution) with redshift up to  $z \approx 0.8$  (see e.g. Wu et al. 1999; Della Ceca et al 2000; Fairley et al. 2000 and reference therein). Fig. 4 shows that the  $L_X - T$  relation ( $L = AT_6^\alpha$  where  $T_6 = T/6$  keV,  $\alpha = 2.02 \pm 0.40$  and  $A = (1.71 \pm 0.21) \times 10^{44} h^{-2}$  erg s $^{-1}$ ) from Markevitch (1998) requires a  $3\sigma$  lower limit of  $T > 4$  keV and  $z > 0.4$ , while the  $1\sigma$  limits require  $T > 7.5$  keV and  $z > 0.65$  if no evolution is assumed. The best fit value of 0.85 obtained from *Chandra* spectrum (dot in Figure 4) is consistent with the unevolving  $L_X - T$  relation.

(3) K-band imaging has shown that 1WGA J1226.9+3332 has a galaxy at  $K=15.5$ . If this source is a first ranked cluster elliptical with  $M_K = -26.7 \pm 0.5$  (Collins & Mann 1998), then, assuming negligible K-correction,  $q_0 = 0.5$  and  $H_0 = 50$  km s $^{-1}$  Mpc $^{-1}$  as in Collins & Mann (1998), it has  $z = 0.68^{+0.30}_{-0.19}$  (dotted lines in Fig. 4).

(4) the color of the K-band galaxies is extremely red, with none bluer than  $R-K \sim 4.5$  and a maximum  $R-K = 6.5$ . Only a unevolving elliptical galaxy at  $0.7 < z < 1.5$  or a Sbc galaxy at  $z > 1.1$  can have such a red color (Coleman, Woo & Weedman, 1980). Using the more accurate  $R-K \sim 5.1 \pm 0.3$  of the first ranked elliptical we can restrict the redshift range to  $0.75 < z < 1.0$  (red lines in Fig. 4).

Using all these constraints we conclude that 1WGA J1226.9+3332 is a distant cluster of galaxies with a most probable redshift of  $0.85 \pm 0.15$  and not smaller than  $z = 0.65$ .

This gives  $kT = 10^{+4}_{-3}$  keV and implies an X-ray luminosity, determined in a  $r = 120''$  aperture, of  $L_{X(0.5-10\text{keV})} = 1.3^{+0.16}_{-0.14} \times$

$10^{45}$  erg s $^{-1}$ , corresponding, for  $z = 0.85$ , to a bolometric  $L = (2 \pm 0.2) \times 10^{45}$  erg s $^{-1}$ . Our estimated redshift is similar to the spectroscopic  $z = 0.89$  found by Ebeling et al. (2001).

The blank field X-ray source 1WGA J1226.9+3332 is thus a highly luminous and massive high redshift cluster and a useful source to determine the evolution of the clusters X-ray luminosity function (e.g. Rosati et al., 1998). Since models in the direction of low  $\Omega$  universe (with or without cosmological constant) (e.g. Henry 2000, Borgani & Guzzo 2001) predict a higher density of high redshift clusters compared to high  $\Omega$  models, finding hot high redshift clusters has a strong leverage on cosmological models.

Since such high luminosity, high redshift clusters should be rare, the relative ease with which this discovery was made is potentially of great significance. The search for high  $F_X/F_V$  sources ('blanks'), sampling a large area of the sky, is an efficient method of finding very luminous high redshift clusters; serendipitous typical flux limited surveys can find (and found) plenty of  $z > 0.6$  clusters, but they are inefficient at finding such luminous clusters because they cover relatively small areas ( $\sim 100$  deg $^2$ ). This methodology is a useful complement to serendipitous flux limited surveys.

We gratefully acknowledge the work by the whole *Chandra* team in making *Chandra* a great success and the staff of CXC for the rapid reprocess of the data and the CIAO data analysis software. We are grateful to M. Markevitch for making his data available in electronic form and for his prompt answers to ACIS background related questions. We thank M. Massarotti, R. Della Ceca, M. Chiaberge, S. Borgani and S. Andreon for useful discussion. IC thanks A. Fruscione, F. Nicastro and A. Siemiginowska for a quick introduction to CIAO. We are also grateful to the staffs of NASA-IRTF and FLWO.

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Labo-

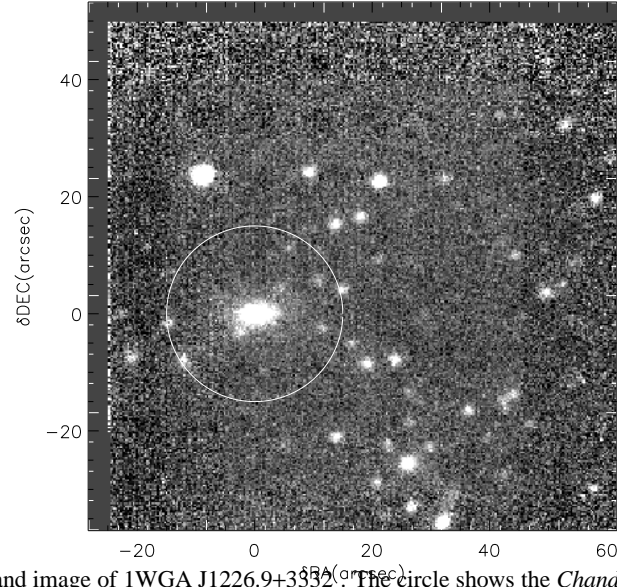


FIG. 5.— K-band image of 1WGA J1226.9+3332. The circle shows the *Chandra* X-ray core radius of 18''.

ratory, CalTech, under contract with the NASA.

This work was supported by NASA grant GO 0-1086X and

by the Italian MURST (IC and AC). P.M. acknowledges an ESA fellowship.

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TABLE 1  
1WGA J1226.9+3332 OBSERVATIONS

| Energy Band | Instrument     | Date        | Exposure<br>(ks) | Coordinates<br>(J2000)          | Offset <sup>a</sup><br>( $\eta$ ) | Count Rate<br>(Counts s <sup>-1</sup> ) | Flux (units)  |
|-------------|----------------|-------------|------------------|---------------------------------|-----------------------------------|---|---|
| X-ray       | <i>Chandra</i> | Jul 31 2000 | 9832.3           | 12 26 58.2 +33 32 48.28         | 0.0                               | $0.107 \pm 0.006^b$                     | $8.03 \times 10^{-13}$ (erg cm <sup>-2</sup> s <sup>-1c</sup> ) |
| R-band      | SAO 48in       | Feb 02 1997 | 900              | 12 26 58.2 +33 32 48.7          | 0.87                              | —                                       | $20.4 \pm 0.2$ (Mag.)   |
| K-band      | IRTF           | Jan 31 2000 | 1200             | 12 26 58 +33 32 48 <sup>c</sup> | 2.0                               | —                                       | 15.5 (Mag.)   |
| Radio       | FIRST          | —           | —                | 12 26 58.19 +33 32 48.61        | 0.79                              | —                                       | $3.61 \pm 0.18$ (mJy at 1.4 GHz)                                |

<sup>a</sup> Offset from *Chandra* position

<sup>b</sup> [0.5-10 keV] in a circle with  $r=120''$  computed from the spectral model within sherpa <sup>c</sup> Due to the lack of bright stars in the K-band image, we obtained an estimate of the position using the objects in common with the R image.